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# Reef response to sea-level and environmental changes during the last deglaciation: Integrated Ocean Drilling Program Expedition 310, Tahiti Sea Level

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**Reef response to sea-level and environmental changes  
during the last deglaciation.  
IODP Expedition 310 “Tahiti Sea Level”.**

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## **Abstract**

The last deglaciation has been characterized by a rapid sea-level rise and coeval abrupt environmental changes. The Barbados coral reef record suggests that this period has been punctuated by two brief intervals of accelerated melting (Melt Water Pulses), occurring at 14.08-13.61 and 11.4-11.1 ka, superimposed on a smooth and continuous rise of sea level. Although their timing, their magnitude, and even their existence have been actively debated, those catastrophic sea-level rises are thought to have induced distinct reef drowning events.

The reef response to sea-level and environmental changes during the last deglacial sea-level rise at Tahiti is reconstructed based on a chronological, sedimentological and paleobiological study of cores drilled through the relict reef features occurring on the modern fore-reef slopes during IODP Expedition 310, **complemented by results obtained on cores drilled on the Papeete reef.**

Changes in the composition of corallgal assemblages coincide with abrupt variations in reef growth rates and characterize the response of the upward-growing reef pile to a non-monotonous sea-level rise and coeval environmental changes.

Reefs accreted continuously between 16 and 10 ka, mostly through aggradational processes, at growth rates averaging  $10\text{mm.yr}^{-1}$  and no cessation of reef growth, even temporary, has been evidenced. The sea-level jump during MWP-1A induced a backstepping of shallow water coral assemblages, a gradual deepening and an incipient reef drowning. The Tahiti reef record does not support the occurrence of an abrupt reef drowning event coinciding with a sea-level pulse during the time interval corresponding to MWP-1B at Barbados.

Keywords : IODP, sea level, last deglaciation, reef growth, Tahiti, submerged reef features, reef drowning, meltwater pulses.

## Introduction

Studies of coral reef records from the last deglaciation (23-6 ka) are of pivotal importance in constraining the timing and magnitude of rapid sea-level rise and related abrupt environmental changes, but also in unravelling the reef response to dramatic environmental perturbations.

Only four reef sequences accurately dated and attributed to times reflecting the Holocene-Pleistocene boundary have been previously investigated by drilling, i.e. Barbados (26-7 ka ; Fairbanks, 1989; Bard et al., 1990 ; Peltier and Fairbanks, 2006), Papua New-Guinea (13-6 ka ; Chappell and Polach, 1991; Edwards et al., 1993), onshore Tahiti (13.85-2.38 ka ; Bard et al., 1996, 2010) and Vanuatu (23-6 ka ; Cabioch et al., 2003). However, the abrupt and significant environmental changes that accompanied the deglacial sea-level rise have been barely investigated so that the accurate reconstruction of the event is obscured.

The Barbados record suggests that the last deglaciation was punctuated by two brief intervals of extremely rapid sea-level rise (Melt Water Pulses – MWP-1A and 1B occurring at

14.08-13.61 and 11.4-11.1 ka respectively) of up to 16 m in less than 500 yrs during MWP-1A. MWPs were originally detected as hiatuses between three separate submerged reef features, each of these segments being offset from the next and coinciding with the interpreted reef drowning events thus hampering the accurate reconstruction of the reef response to sea-level change.

Although the timing, magnitude, and even the existence of MWPs have been actively debated (see review in Deschamps et al.), those catastrophic sea-level jumps, are thought to have induced reef drowning events (Blanchon and Shaw, 1995) that might have been followed by major non-constructional periods (Montaggioni, 2005).

This study deals with reef response to sea-level and environmental changes between 16 and 10 ka, based on the more extensive and continuous coral reef offshore record obtained at Tahiti during IODP Expedition #310.

## Setting

Unlike islands located in active margins, like Barbados or Vanuatu, Tahiti is a volcanic island characterized by slow and regular subsidence rates estimated at  $0.25 \text{ mm.yr}^{-1}$  (Bard et al., 1996) and located at a considerable distance from the major former ice sheets (“far-field” site). It therefore provides an ideal setting to reconstruct sea-level rise and to constrain short-term environmental changes that are thought to have punctuated the period between the Last Glacial Maximum and the present.

During IODP Expedition 310, 37 holes were drilled at 22 sites (M0005–M0026) along transects at depths ranging from 41.6 to 117.5 meters below sea level (mbsl) in three areas around Tahiti: offshore Faava, Maraa and Tiarei (Camoin et al., 2007a,b) (Fig. 1). The drilling targets were mostly focused on the two prominent terraces that occur at 50-60 and 90-100 mbsl respectively, which support abundant relict reefs that rise at 30 to 45 m above the sea floor (Camoin et al., 2006). The Tiarei area is characterized by the occurrence of two successive

ridges seaward of the living barrier reef at 60 and 90-100 mbsl (Fig. 2). Those ridges comprise a line of isolated or fused pinnacles that were previously recognized as reef features exhibiting an original irregular morphology, and corresponding therefore to primary records of reef development (Camoin et al., 2006). Similar reef features have been recognized on many modern reef slopes (see reviews in Dullo et al., 1998; Camoin et al., 2006 and Beaman et al., 2008) but were drilled previously only in Barbados (Fairbanks, 1989).

More than 600 m of reef cores displaying an exceptional recovery (>90% ; Inwood et al., 2008) and quality were retrieved and, combined with the high-resolution downhole measurement data, correspond therefore to unique archives to resolve in unprecedented detail the reef response to the last deglacial sea-level rise and coeval environmental changes.

### **Composition of the last deglacial reef sequence**

The fossil reef systems around Tahiti are composed of two major chronological and lithological sequences (Camoin et al., 2007a,b) which are attributed to the last deglaciation (Deschamps et al., submitted) and to older Pleistocene time windows (Thomas et al., 2009 ; Iryu et al., 2010). The contact between those sequences is characterized by the occurrence of an irregular unconformity which ranges in depth from 94 to 122 mbsl on the Tiarei inner and outer ridges (Fig. 1), thus indicating a rugged morphology of the pre-glacial surface prior to the reef initiation and growth during the last deglaciation.

The last deglacial sequence is mostly composed of coral frameworks generally thickly encrusted by coralline algae that are locally associated with encrusting foraminifers and sessile vermetid gastropods. The dominant coral morphologies (branching, robust branching, massive, tabular, foliaceous, and encrusting) and the abundance of associated builders and encrusters determine distinctive frameworks displaying a wide range of internal structures, from loose to dense frameworks. The primary cavities between coral colonies are partly to entirely occluded

by abundant microbialite crusts, ranging in thickness from a few centimeters up to 20 cm and displaying a wide range of growth forms (Seard et al., 2011). The coralgal frameworks are associated or interlayered in places with skeletal limestone, volcanoclastic sediments and/or loose skeletal sediments (rubble, sand and silt) which represent only a minor component of the Tahiti cores, implying a low skeletal production of the frameworks.

Six distinctive coralgal assemblages have been identified in the Tiarei cores and are indicative of a range of modern reef environments, from the reef crest to the reef slope (see (Camoin et al., 2007a,b; Abbey et al., 2011 and enclosed references), in agreement with earlier studies on Tahiti and other Indo-Pacific reef sites (see review in Montaggioni, 2005). They form a continuum and most of them overlap in bathymetry (Fig. 1).

The robust branching *Pocillopora*/massive *Montipora* (PM) assemblage includes a coralline algal association dominated by *Hydrolithon onkodes* and *Mastophora pacifica*, and characterizes reef edge environments in water depths less than 10 m. The assemblage characterized by robust branching *Acropora* of the *robusta-danai* group (AP) which dominates frameworks younger than 12 ka both in Papeete (Fig. 1) and Maraa drill cores does not occur in the Tiarei cores, probably in relation with local environmental conditions in that area.

The other end member of that continuum consists of an encrusting agaricids and faviids (AFM) assemblage bearing a coralline algal association dominated by *Mesophyllum funafutiense* and *Lithoporella*, indicating depths greater than 20 m. The massive *Porites* (mP) and the tabular *Acropora* (tA) assemblages tend to dominate semi-exposed to sheltered environments of the upper and mid- forereef slope and backreef zones, within the 0-25 m depth range for the mP and not deeper than 20 m, with a common occurrence between 5 and 15 m for the tA. The depth range of these two assemblages can be restricted to 5-10 m when thick *Hydrolithon onkodes* crusts are associated.

Branching *Porites* are the most abundant corals observed in the Tiarei cores and dominate two distinctive assemblages typifying semi-exposed to sheltered environments of the mid-foreereef, inner reef flat and backreef zones typified by moderate energy conditions with reduced light intensity. The branching *Porites/Pocillopora* (PP) assemblage developed at depths up to 20 m, but more frequently between 5 and 10 m, as indicated by the occurrence of thick *Hydrolithon onkodes* crusts. The branching *Porites*/encrusting *Porites* and *Montipora* (PPM) assemblage probably developed in a larger depth range (5-25 m), as indicated by the associated coralline algae characterizing either shallow water, i.e. less than 10 m (*Hydrolithon onkodes* and *Mastophora pacifica*), or deeper water environments, i.e. between 15 and 25 m (*Lithophyllum prototypum* - *Mesophyllum erubescens* - *Lithothamnion prolifer* assemblage).

### Reef response to sea-level and environmental changes

The U-series and  $^{14}\text{C}$  analyses carried out on the corals from the IODP cores provided reliable and stratigraphically consistent ages ranging from 16 to 10 ka, and complement the results obtained on the Papeete drill cores which encompass the 13.8-3 ka time window (Bard et al., 1996 ; Montaggioni et al., 1997 ; Camoin et al., 1999 ; Cabioch et al., 1999). The study of the offshore drill cores has demonstrated the occurrence of MWP-1A with a well-constrained chronology (14.65 to 14.3 ka) and amplitude (16±2 m ; Deschamps et al.). In contrast, recent investigations on onshore drill cores report a relatively smooth sea-level rise, with no significant acceleration during the time interval corresponding to MWP-1B at Barbados (Bard et al., 2010). All ages reported in this paper are in calendar years BP.

The anatomy of reef systems from the Tiarei area indicates that their development has been controlled by the progressive flooding of the Tahiti slopes and the coeval increase in accommodation. At all drill sites, the cored reef sequences do not display any unconformity,



implying that reefs accreted continuously mostly through aggradational processes between 16 and 10 ka.

The formation of the successive ridges, which characterize that area, is seemingly related to local topographic and substrate conditions provided by the older Pleistocene carbonate sequence in a region dominated by volcanoclastic sediments. No similar ridges were reported in other drilled areas around Tahiti.

On the outer ridge of the Tiarei area, the last deglacial reef sequence provides stratigraphically consistent ages ranging from  $16.09 \pm 0.04$  ka at 121 mbsl in Hole M0009B to  $10.91 \pm 0.13$  ka at 82.7 mbsl in Hole M0021B (Fig. 1), with an overall aggradation rate of  $7.5 \text{ mm.yr}^{-1}$ . On the inner ridge, it is 24 to 29 m-thick in Holes 23A and 23B respectively and ranges in age from  $14.31 \pm 0.04$  to  $10.59 \pm 0.10$  ka (Fig. 1), implying an overall aggradation rate of  $6.5 \text{ mm.yr}^{-1}$ . However, the major part of the reef accretion curve expresses maximum growth rates exceeding  $10 \text{ mm.yr}^{-1}$  during the 16-10 ka time window. At each individual drill site the last deglacial reef sequence is continuous and displays a general deepening-upward trend (Fig. 1). Changes in the composition of coralgall assemblages coincide with abrupt variations in reef growth rates (Fig. 2) and characterize the response of the upward-growing reef pile to a non-monotonous sea-level rise and coeval environmental changes which may have fluctuated near the tolerance limits of the involved coral assemblages.

The pre MWP-1A period (16 to 14.65 ka) is characterized by a moderate rise in sea level with a magnitude of ~10 m, implying an average rate of  $7.4 \text{ mm.yr}^{-1}$ . The first assemblage to colonize the Pleistocene carbonate substrate corresponds to the PM assemblage which developed during the 16.09-~15.5 ka time window (Fig. 1). The subsequent development of the mP assemblage, comprised of turbidity-tolerant corals, during a ~500 years period (i.e. from  $15.23 \pm 0.03$  to  $14.75 \pm 0.03$  ka) at the deepest sites of the outer margin probably typifies an

increase in terrigenous inputs. Reef growth rates range from 6 to 9 mm.yr<sup>-1</sup> during the pre-MWP-1A period and imply that reefs kept pace with the rising sea level (Fig. 2).

MWP-1A occurred in ~350 years (14.65-14.3 ka time window) and induced a sea-level jump of 16±2 m (Deschamps et al.). The reef response to this accelerated rise in sea level is characterized by significant changes in coral assemblages, especially involving the development of loose frameworks of fast-growing corals (PP assemblage) with a high initial porosity (averaging 50%) at the deepest sites of the outer margin (Site 9). The PP assemblage aggraded at average vertical rates lower than 10 mm.yr<sup>-1</sup> during MWP-1A, implying that reef growth was insufficient to balance the sea-level rise which ultimately induced a gradual deepening and an incipient reef drowning ; however no cessation of reef growth, even temporary, has been evidenced during this period. The sea-level jump during MWP-1A was sufficient to displace the PM assemblage out of its 10 m or less habitat zone and to induce its relocation upslope, on the inner part of the outer ridge (Site 21) and then on the inner ridge (Site 23 ; Fig. 1), implying a backstepping of this shallow water assemblage at average rates greater than 700 mm.yr<sup>-1</sup> during that time window. At the end of MWP-1A, ca 14.3 ka, the Tiarei reefs exhibited a clear lateral zonation from the inner ridge characterized by the growth of the PM shallow water assemblage, to the outer ridge characterized by the development of deeper water coral assemblages (PP and PPM).

The reef sequence from the inner ridge records a continuous reef growth from 14.3 to 11.2 ka characterized by a gradual deepening through time typified by a vertical succession involving the PM and the PP assemblages for more than 1500 years, followed by the development of tA, mP and PPM assemblages, while the coeval outer ridge sequences are mostly comprised of PPM and AFM assemblages. The transition from mP to AFM coral assemblages may characterize a slight deepening (i.e. a few meters) at ~11.2 ka, within the timing of MWP-1B (11.4-11.1 ka ; Peltier and Fairbanks (2006). However, no significant acceleration during the

time interval corresponding to MWP-1B at Barbados is recorded in the Papeete cores (Bard et al., 2010). The continuous development of shallow-water coral assemblages, i.e. at depths less than 6 m, at nearly constant reef accretion rates for the last ~13.9 ka (Montaggioni et al., 1997 ; Camoin et al., 1999 ; Cabioch et al., 1999) does not support the occurrence of an abrupt reef drowning event coinciding with a sea-level pulse of ~15 m implying an apparent rise of 40 mm.yr<sup>-1</sup> as it was deduced from the Barbados record (Blanchon and Shaw, 1995).

At all sites, the upper part of the last deglacial sequence corresponds to the development of the slowly growing (3 mm.yr<sup>-1</sup> in average) AFM assemblage at depths generally exceeding 20 m, and ranging in age from 12.32±0.03 to 10.59±0.10 ka on the outer and inner ridges respectively. The top 2–3 m of the sequence exhibit classic platform drowning signatures characterized by a suite of biological, sedimentary and diagenetic features, including extensive bioerosion, manganese and iron staining of the rock surface, and submarine hardgrounds. This condensed deep-water sequence developed when the reef features dropped to a depth where carbonate production was limited as a consequence of continued sea-level rise and coeval environmental changes (e.g. light availability, water quality) during Holocene time (see also Camoin et al., 2006).

## Conclusions

The chronological, sedimentological and paleobiological study of cores drilled through the relict reef features occurring on the Tahiti fore-reef slopes and through the modern reefs of Papeete, indicate that reefs accreted continuously, mostly through aggradational processes, at growth rates averaging 10 mm.yr<sup>-1</sup> during the 16-10 ka time interval that encompasses MWPs that have been detected in the Barbados coral reef record.

The overall reef sequence typifies the backstepping of shallow-water corallgal assemblages. The two Tiarei ridges are characterized by deepening-upward sequences, while the

Papeete sequence is characterized by the continuous development of shallow-water coral assemblages.

The sea-level jump during MWP-1A,  $16 \pm 2$  m of magnitude in ~350 years, induced a backstepping of shallow water coral assemblages. Reef growth was insufficient to balance the sea-level rise which ultimately induced a gradual deepening and an incipient reef drowning ; however no cessation of reef growth, even temporary, has been evidenced during this period.

The Tahiti reef record does not support the occurrence of an abrupt reef drowning event coinciding with a sea-level pulse of ~15 m, implying an apparent rise of  $40 \text{ mm.yr}^{-1}$  during the time interval corresponding to MWP-1B at Barbados.

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## FIGURE CAPTIONS

Figure 1. Lithologies, selected U-series and  $^{14}\text{C}$  ages, and distribution of the coralgall assemblages at Papeete and Tiarei drill sites. Top right : Seismic line across the Tiarei area displaying the two ridges drilled during the IODP Expedition 310 and the modern reef. Insert map : offshore (Tiarei, Maraa and Faaa) and onshore (Papeete P cores) drill sites at Tahiti. Coral assemblages – AP : branching *Acropora* and *Pocillopora* ; PM : branching *Pocillopora*/massive *Montipora* ; mP : massive *Porites* ; tA : tabular *Acropora* ; PP : branching *Porites*/*Pocillopora* ; PPM : branching *Porites*/encrusting *Porites* and *Montipora* ; AFM : encrusting agaricids and faviids.

Figure 2. A. - Reef accretions curves based on data obtained both on the IODP Tiarei (offshore) and the Papeete (onshore) drill sites. B. - Evolution of the average growth rates of the successive coral assemblages during the 16-10 ka time window for the Tiarei and the Papeete drill sites. Timing of the Meltwater pulses (MWP) based on data from Deschamps et al. (submitted) and Peltier and Fairbanks (2006) for the MWP-1A and MWP-1B respectively. Abbreviations of coral assemblages : see Fig. 1.





